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Analysis of spatial and temporal distribution of grassland yield under grassland ecological subsidy policy

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The Three River Headwater Region is an ecologically sensitive and fragile area. The analysis of long-term grassland yield changes, as well as the impact of climate and topography on grassland yield is of great significance to grassland ecological protection and the implementation of ecological subsidy policy in the Three River Headwater Region. Based on the grassland yield data from 2011 to 2016, this paper analyzed the spatial and temporal distribution of grassland yield and variations in grass production since the implementation of the grassland ecological subsidy policy in Qinghai Province by using linear regression analysis, coefficient of variation, and biased correlation analysis. Additionally, the effects of three meteorological factors, namely, annual mean temperature, annual precipitation, and annual evapotranspiration, and two terrain factors, namely, elevation and slope, on grassland yield were analyzed. The results were as follows: (1) The grassland yield in the Three River Headwater Region gradually decreased from east to west; From the classification space of grassland, it can be seen that with the alpine meadow as the boundary, the spatial distribution of grassland yield in the Three River Headwater Region forms an obvious watershed. (2) The overall grassland yield in the Three River Headwater Region increased first and then decreased, but the overall change trend was not large. (3) The positive correlation between the average annual grassland yield and the average annual precipitation in the Three River Headwater Region was nearly 58%, which was distributed in concentrated contiguous areas, and the eastern and northwestern parts of Three River Headwater Region were more concentrated; The area of positive correlation with annual mean temperature is nearly 48%. The positive correlation between the area and the annual average evapotranspiration is nearly 48%. (4) The grassland yield in the source area of Three River Headwater Region increased first and then decreased with the increase of elevation; The grassland yield increased with the increase of slope. In summary, since the grassland ecological reward policy has been carried out in Qinghai Province, the grassland yield in the Three River Headwater Region has been relatively stable in time and space, positively correlated with precipitation, insignificantly correlated with temperature and evapotranspiration, and highly correlated with elevation and slope.

Keywords Three river headwater region, Grassland yield, Linear regression analysis, Coefficient of variation, Biased correlation analysis, Meteorological factors, Terrain factors

Grassland is one of the most important ecosystems in the Headwater Region. It has an important role for supplying water and ecological stability in China. In recent decades, the importance of grassland degradation has become more serious. This is mainly caused by climate change and overgrazing. Degraded grasslands reduce the quality of the ecosystem and make it harder for local people to raise livestock^{1–3}. “Sanjiangyuan” is the source of the three rivers (the Yellow River, the Yangtze River, and the Lancang River) and is also one of the most sensitive ecosystems in China¹. It serves as an ecological natural barrier for the ecological and

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sustainable development of the middle and lower reaches of China's rivers. However, due to the limitations of the instability of high-altitude ecosystems and the weak self-regulation mechanisms, the Sanjiangyuan region is greatly affected by climate change^{2–5}, which has a significant impact on the grass production in the region. To deal this problem and difficulties, the Chinese government has fulfilled the Grassland Ecological Reward and Subsidy Policy in 2011. This policy purposes to reduce grazing pressure and restore degraded grassland in order to promote a balance between grass and livestock^{4,5}. The combination of the grassland degradation situation and livestock carries capacity of the province Sanjiangyuan to conduct a grass-livestock balance policy, preserving the grassland ecological environment. After the first round of grassland ecological compensation policy, the livestock overloading rate has dropped to 3.74%, and the overall goal of “grass-livestock balance” has been achieved¹¹. Grass production estimation is a prerequisite for implementing the grass-livestock balance, and studying the spatial variation of grass production and analyzing its influencing factors has practical significance for grassland ecological protection and the implementation of grassland ecological compensation policy.

Grassland forage production refers to the total number of plants per unit area of grassland in a certain period of time, which is one of the important parameters determining the livestock carrying capacity of grassland. Zhang YaXian et al.¹² used MODIS-NDVI products and ground sampling data to establish a forage yield estimation model and conducted spatial trends and its impact on precipitation pattern analysis of forage yield from 2006 to 2013. Taylor et al.¹³ used NDVI to monitor and analyze grassland productivity, and found that it was closely related to aboveground biomass. Zhang Lu et al.¹⁴ conducted a temporal-spatial analysis of forage yield in Xilinhot from 1991 to 2016 and studied its response to meteorological factors, showing that the overall trend of forage yield in the study area was decreasing, and the correlation with annual precipitation was different depending on land cover, and there was no significant correlation with annual mean temperature. Luo ZhenTang et al.¹⁵ analyzed the main factors affecting the forage yield of high-altitude grassland as the forage grew, and the factors affecting it also changed. Han BingHong et al.¹⁶ conducted a quantitative analysis of the change in forage yield in the Sanjiangyuan region from 2003 to 2017, and found that its spatial and temporal distribution had obvious heterogeneity, and the yield was not determined by a single meteorological condition.

Currently, there has been less research on the changes in grass production in the Sanjiangyuan area after the grassland ecological subsidy policy, and the analysis of terrain factors and meteorological multi-factors is also relatively less. Therefore, this study, based on the grass production data of the Sanjiangyuan area from 2011 to 2016, uses linear regression analysis, coefficient of variation, partial correlation analysis, etc. to comprehensively analyze the temporal and spatial evolution laws of grass production in the Sanjiangyuan area over the past 5 years since the full implementation of the grassland ecological protection subsidy policy in Qinghai Province, and its relationship with climate and terrain factors, in order to provide scientific basis for the ecological governance and sustainable management of the Sanjiangyuan area.

Data and methods

Overview of the study area

Sanjiangyuan is located in the southern part of Qinghai Province, in the heart of the Qinghai-Tibet Plateau, with the Kunlun Mountains and Buqing Mountains to the north, Tanggula Mountains to the south, the Yellow River bank to the east, and the Zulkun Ula Mountains, Ulan Ula Mountains, and the Kekexili area to the west. The area is mainly mountainous with complex terrain, with an average altitude of 3,500–4,800 m, featuring a low-to-the-east and high-to-the-west topographic characteristic. Most of the mountains are oriented northwest-southeast, which profoundly affects the vegetation development and water and heat conditions in Sanjiangyuan, with 49.2% of the total Yellow River discharge, 25% of the total Yangtze River discharge, and 15% of the total Lancang River discharge originating from this area.

The main types of grassland in the Three River Headwater Region are alpine meadow, alpine steppe, and mountain meadow. The alpine meadow is the most widely distributed and has a vital impact in maintaining ecosystem function and water conservation. The mountain meadow has relatively higher productivity and is often found in lower elevations with better soil and moisture conditions. The alpine steppe is generally found in drier areas and has lower vegetation cover and forage yield. These grassland types respond differently to climate and terrain conditions, which influences the spatial variation of grassland yield in the region.

Experimental data sources

The grass production within the study area was obtained using high-resolution Landsat series remote sensing images from 2011 to 2016. The cross-validation was used to ensure the reliability of the remote sensing-derived grassland yield data. It was cross-validated the estimates with field sampling data and statistical records from regional grassland monitoring reports. This comparison would confirm that the yield values obtained from Landsat imagery using geographically weighted regression (GWR) and invers distance weighting (IDW) methods were a reasonable range and reflected actual spatial patterns in the study site. The GWR^{17,18} and the IDW method were used to obtain it. The spatial resolution was 30 m. The topographic data used in the study came from the Geographic Information Cloud, with a resolution of 30 m. The GWR was adopted to analyze spatial relationships. This method allows the model coefficients to vary across space, which is suitable for the Sanjiangyuan region with different natural conditions and complex variables. The GWR is an effective model in capturing the local influence of environmental factors. The GWR was computed as follows:

$$y_i = \beta_0(u_i, v_i) + \sum \beta_k(u_i, v_i) * x_{ik} + \varepsilon_i \quad (1)$$

Where: y_i is the dependent variable at location i , x_{ik} indicates the k -th independent variable at location i , $\beta_k(u_i, v_i)$ is the coefficient for the k -th independent variable at spatial coordinates (u_i, v_i) , $\beta_0(u_i, v_i)$ shows the intercept

at location i , and ε_i is the random error term. The coefficients $\beta_k(u_i, v_i)$ are estimated locally for each location using weighted least squares, where observations closer to the location have more influence.

Several preprocessing and data quality control steps were applied prior to analysis for ensuring data quality and consistency. For analyzing the Landsat images used for the grass yield estimation, standard preprocessing was used. This method includes cloud masking, radiometric calibration, and atmospheric correction. Multi-scene images were then mosaicked and clipped to match the study area boundaries. Pixels with persistent cloud cover or poor image quality were excluded from the analysis.

The meteorological data obtained from NASA's official database were compared with available ground station data from Qinghai Province. The value ranges between the datasets showed good consistency, which supported the suitability of the NASA data for our analysis. These validation steps confirmed the credibility of the input data used in our modeling process. The interquartile range (IQR) analysis was used to detect outliers. It excluded data points that were extreme outliers and outside ecologically plausible ranges, especially in regions known to be influenced by sensor error or atmospheric interference.

To ensure consistency in spatial analysis, bilinear interpolation method was used to resample the meteorological data originally provided at 500 m resolution to 30 m resolution. This method provides smoother transitions between values and is suitable for continuous data such as temperature and precipitation. After resampling the meteorological data, all datasets shared the same spatial resolution (30 m), which allowed for accurate pixel-level correlation and regression analyses across grassland yield, meteorological, and topographic variables.

Research methods

Spatial dynamic analysis

In this study, several statistical methods were used based on the data characteristics and research objectives. Linear regression analysis was applied to investigate the grassland yield changes in a long period of time. This method was chosen because it is straightforward and useful to observe and to interpret. The basic assumptions of linear regression, such as normal distribution of residuals, homoscedasticity, and independence, was checked using residual plots and normality tests.

Using linear regression analysis, the grass production in the study area was dynamically analyzed to grasp its change trend. The formula of linear regression analysis method is as follows:

$$c = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (3)$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (4)$$

In the formula, c represents the dynamic trend value of forage production; x represents the independent variable of spatial dynamic analysis of forage production, which is the year; \bar{x} represents the average value of the independent variable of spatial dynamic analysis of forage production; y represents the dependent variable of spatial dynamic analysis of forage production, which is the annual forage production data; \bar{y} represents the average value of the dependent variable of spatial dynamic analysis of forage production. The Variance Inflation Factor (VIF) was calculated to reduce the risk of multicollinearity among all independent variables before running regression and correlation models. All VIF values were below 5, which indicated that multicollinearity was not a problem in our analysis. The VIF was calculated as follows:

$$\text{VIF} = 1/(1 - R^2) \quad (5)$$

Where, R^2 is the result from a regression of one independent variable on all the other independent variables. The VIF value more than 5 indicates there may be a problem with multicollinearity.

The forage production in the Sanjiangyuan region was classified into five grades according to the change trend, namely, declining, slightly declining, basically balanced, slightly improving, and improving. The classification scale was adopted from the classification standard in the report on grassland monitoring and evaluation (2011–2015) in Qinghai Province, which was based on the overall change situation in Qinghai Province, as shown in Table 1.

Time dynamic analysis

The time dynamic changes of forage production were analyzed using the coefficient of variation. The coefficient of variation (CV) was used to analyze the variation degree of grassland yield in the time series. Since the CV is the ratio of standard deviation to the mean, it allows us to compare the relative fluctuation in yield across different regions. The larger the coefficient of variation, the more dispersed the values of forage production are, and the greater the fluctuations in forage production over time; the smaller the coefficient of variation, the more compact the values of forage production are, and the more stable the fluctuations in forage production over time. The specific calculation formula is as follows.

Classification of grassland yield variation trend	Grading standard
Decline	< - 100
Slight decline	- 100 to - 20
Fundamental equilibrium	- 20 to 20
Slight improvement	20-100
Improvement	> 100

Table 1. Classification of grassland yield time variation trends.

Classification of grassland yield variation trend	Grading standard
Low fluctuation variation	CV ≤ 0.1
Relatively low fluctuation variation	0.1 < CV ≤ 0.2
Moderate fluctuation variation	0.2 < CV ≤ 0.3
Relatively high fluctuation variation	0.3 < CV ≤ 0.4
High fluctuation variation	CV ≥ 0.4

Table 2. Classification of grassland yield time variation trends.

Correlation classification	Grading standard
Positive correlation	> 0
Negative correlation	< 0
Uncorrelated	0

Table 3. Correlation classification of grassland yield with annual precipitation: annual average temperature and annual evapotranspiration.

$$C_v = \frac{\sigma}{\bar{x}} \tag{6}$$

Where C_v is the coefficient of variation, σ is the standard deviation of forage production, and \bar{x} is the average value of forage production.

Based on the existing research foundation and taking into account the actual situation of the Sanjiangyuan region, the results of the temporal dynamic changes in forage production in the Sanjiangyuan region are divided into five levels: low fluctuation changes, relatively low fluctuation changes, moderate fluctuation changes, relatively high fluctuation changes, and high fluctuation changes¹⁹ (Table 2).

Impact factor analysis

Considering that meteorological conditions²⁰ and topographic conditions are important factors affecting grass production, this paper selected annual mean temperature, annual precipitation, and annual evapotranspiration as three meteorological factors and elevation and slope as two topographic factors as independent variables affecting the spatial pattern of grass production.

The relationship between grass production and annual precipitation, annual mean temperature, and annual evapotranspiration was established. The relationship coefficient was established by using 30*30 m pixel as the analysis unit, reflecting the correlation between grass production and annual precipitation, annual mean temperature, and annual evapotranspiration in the Sanjiangyuan region. The value range is -1 to 1, divided into positive correlation, negative correlation, and no correlation three levels (Table 3). The correlation analysis data were resampled for easy visualization of the spatial correlation between the factors. The relationship coefficient calculation formula is:

$$W_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2 (y_i - \bar{y})^2} \tag{5}$$

In this equation, W_{xy} represents the correlation coefficient between the two variables; x represents the annual mean temperature, precipitation or evapotranspiration; y represents the grass yield; \bar{x} represents the average of the n annual mean temperature, precipitation or evapotranspiration; and \bar{y} represents the average of the n years' grass yield.

Results and analysis

Spatial characteristics and change analysis

The grass production in the Sanjiangyuan region showed a decreasing trend from east to west from 2011 to 2016 (Fig. 1). The grass production in the Kuqa Xili area was significantly lower. From the spatial perspective at the county level, the grass production was relatively high in Zeku County, Xinhong Mongol Autonomous County, Maqin City, Gandê County, Jiuji County, Banma County, Dari County, Yushu City, and Nangqian County. From the spatial perspective of grassland types, it can be seen that the grass production in the Sanjiangyuan region forms a clear watershed with the high-altitude meadow as the boundary, with the average grass production of the mountain meadow type being the highest and the average grass production of the alpine meadow type being the second highest.

According to the decline, slight decline, relatively stable, slight improvement, and improvement in 5 degrees, the overall change in grass production in the Sanjiangyuan area since the first round of grassland ecological subsidy policy was implemented in 2011–2016 was analyzed. Through the analysis, it can be seen that the grass production in the Sanjiangyuan region is relatively stable and the proportion of relatively stable areas is 86.97%. The area of the declining region is relatively small, mainly scattered in Yushu City, Nangqian County, Gonghe County, and Xinghai County. The slight decline area is distributed throughout the Sanjiangyuan area, concentrated in large areas in Gonghe County and Zeke County. The slight improvement area is distributed relatively evenly in the Sanjiangyuan area, with the exception of fewer points in the heart of Kekexili, and other areas are distributed in a point-like manner. The area of the improved area is the smallest, accounting for only 0.003% of the total area (see Fig. 2).

Time characteristics and changes analysis

The average grass production was calculated for the period from 2011 to 2016. From the time characteristics shown in Fig. 3, the average grass production in the Sanjiangyuan region presents an irregular “M” shape, showing a fluctuating trend of increasing first and then decreasing overall. Among them, the average grass production in 2013 was the highest, at 2,266.81 kg/hm², while the average grass production in 2016 was the lowest, at 1,935.98 kg/hm².

From the time series changes (Fig. 4; Table 2), it can be seen that during the implementation period of the first grassland ecological subsidy policy, the relatively lower fluctuation changes in the Sanjiangyuan area accounted for a higher proportion of 51.42%, mainly distributed in the north, west, and east of the Sanjiangyuan area, and the distribution in the south was relatively scattered. The proportion of low fluctuation changes was 30.27%, mainly distributed in the south of the Sanjiangyuan area. The medium fluctuation changes were scattered and patchy distributed in the north of the Sanjiangyuan area. The relatively higher fluctuation changes and high fluctuation changes accounted for a smaller proportion and were scattered. Therefore, from the time series point of view, the grass yield in the Sanjiangyuan area has changed little over time and is relatively stable (see Table 4).

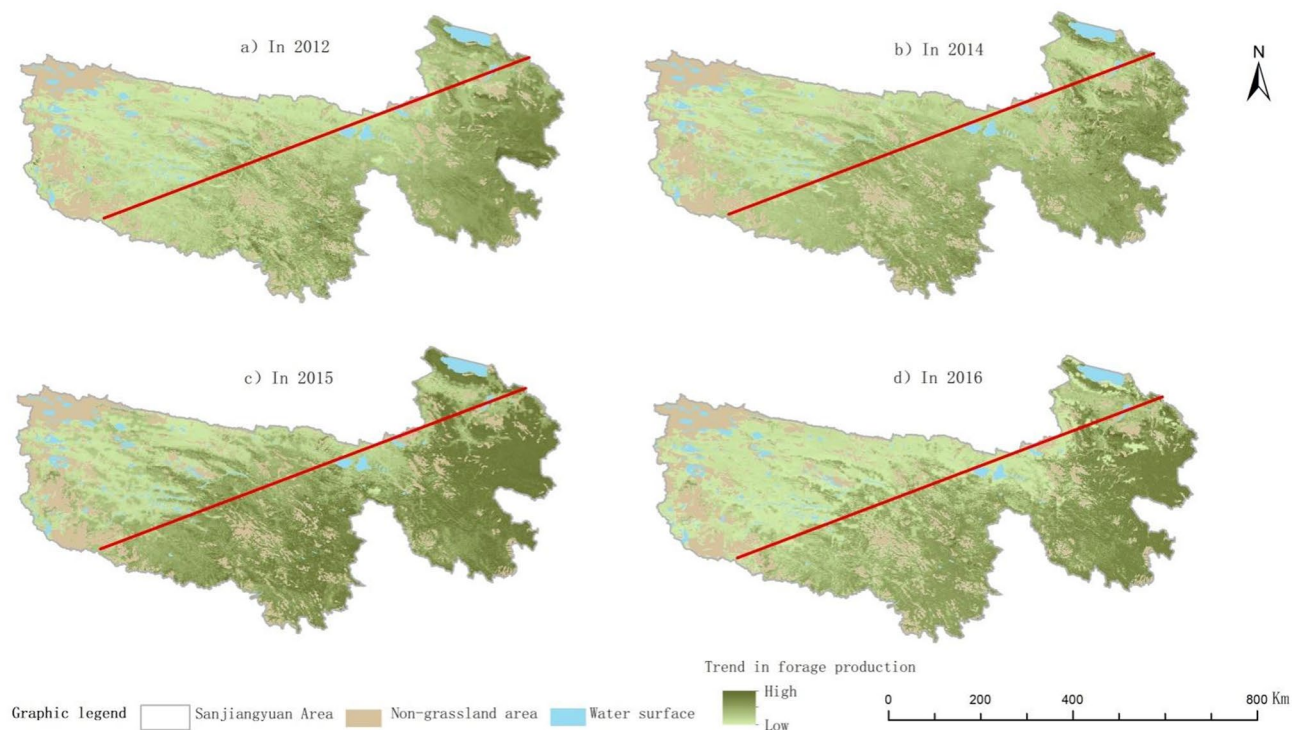


Fig. 1. Spatial distribution of annual grassland yield in three river headwater region. The figure was created using ArcGIS 10.7.(URL: <https://prhj.hemaish.com/arcgis?qhclickid=647c456cf883a414>).

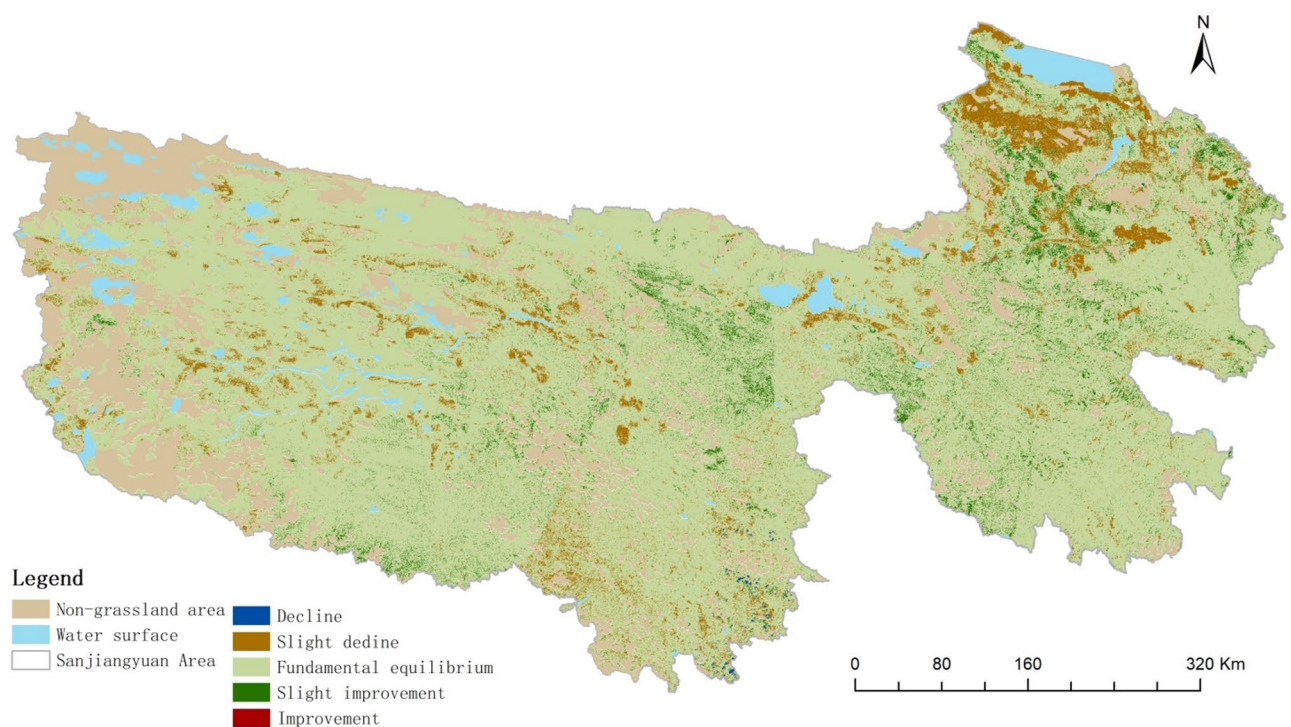


Fig. 2. Spatial variation trend of annual grassland yield in three river headwater region. The figure was created using ArcGIS 10.7.(URL: <https://prhj.hemaish.com/arcgis?qhclickid=647c456cf883a414>).

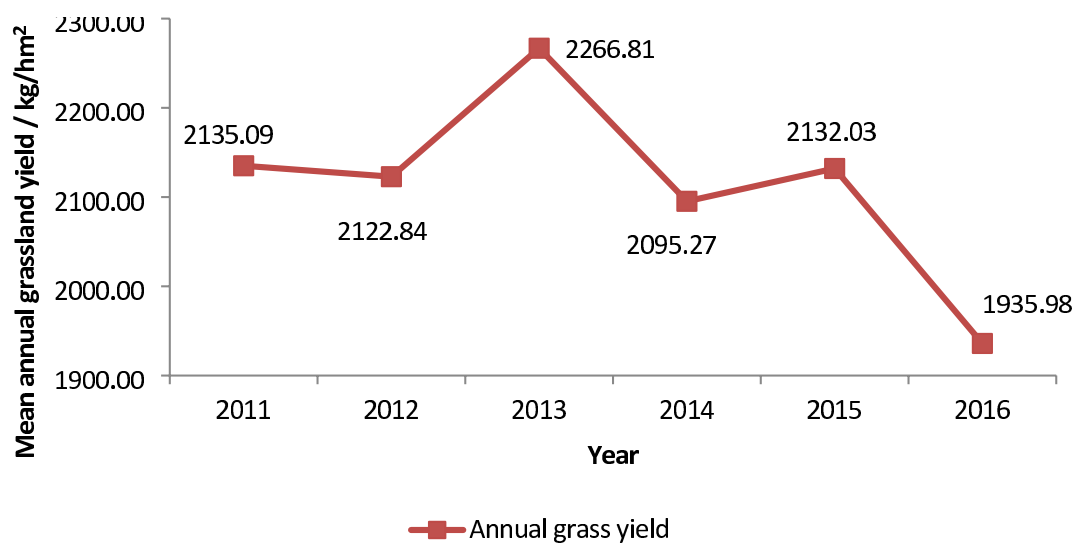


Fig. 3. Line graph of temporal variation of grassland yield in three river headwater region.

The impact of meteorological factors on changes in grass production

Meteorological factors are important driving factors for changes in grass production. In this study, precipitation, temperature, and evapotranspiration were selected as the three meteorological factors. The partial correlation coefficients between grass production and annual precipitation, temperature, and evapotranspiration were calculated for each pixel in the Sanjiangyuan region from 2011 to 2016. During the period from 2011 to 2016, the annual grass production and annual precipitation in the Sanjiangyuan region showed an elastic decline trend, while the annual temperature and annual evapotranspiration showed an overall upward trend (see Fig. 5).

From the spatial perspective (Fig. 6), the area where the annual grass production in the Sanjiangyuan region is positively correlated with the annual precipitation accounts for nearly 58%, with a concentrated and contiguous

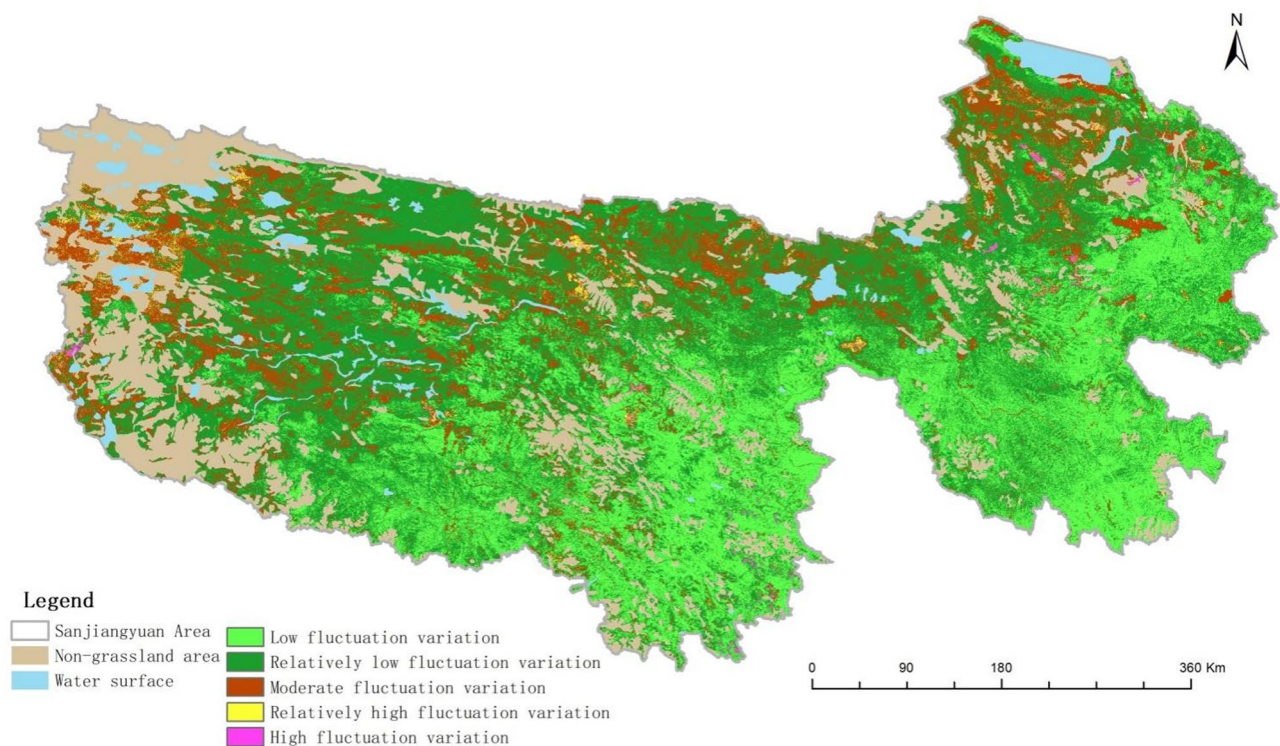


Fig. 4. Spatial distribution of temporal variation of grassland yield in three river headwater region. The figure was created using ArcGIS 10.7.(URL: <https://prhj.hemaish.com/arcgis?qhclickid=647c456cf883a414>).

Volatility degree	Area percentage (%)
Low fluctuation variation	30.27
Relatively low fluctuation variation	51.42
Moderate fluctuation variation	16.53
Relatively high fluctuation variation	1.39
High fluctuation variation	0.39

Table 4. Proportion of time variation of grassland yield.

distribution. The eastern and northwestern parts of the region are more concentrated, while the southern area is relatively less. The area where the annual grass production is negatively correlated with the annual precipitation accounts for nearly 42%, mainly distributed in the southeastern and southern parts of the region. The area where the annual grass production is positively correlated with the annual temperature accounts for nearly 48%, mainly distributed in the central region of the Sanjiangyuan region. The area where the annual grass production is negatively correlated with the annual temperature accounts for nearly 52%, mainly concentrated in the eastern and western regions. The area where the annual grass production is positively correlated with the annual evapotranspiration accounts for nearly 48%, mainly concentrated in the southwestern part of Qinghai Lake and the central region of the Sanjiangyuan region. The area where the annual grass production is not correlated with the annual evapotranspiration accounts for nearly 2%, mainly concentrated in the Koko Nor region of the Sanjiangyuan region and the southwestern part of Qinghai Lake. The area where the annual grass production is negatively correlated with the annual evapotranspiration accounts for nearly 50%, mainly concentrated in the eastern, southeastern, western and central regions, with some distribution in other areas. It can be seen that the annual precipitation is positively correlated with the annual grass production, while the annual temperature and annual evapotranspiration are not significantly correlated with the annual grass production, but their effects on the annual grass production are consistent.

The influence of terrain factors on changes in grass production

Elevation mainly affects the distribution of temperature and temperature, and the Qinghai-Tibetan Plateau is dominated by mountainous terrain, with mountains stretching out, high elevations, and complex terrain. Different elevation ranges have different effects on grass production in the Sanjiangyuan region. As shown in



Fig. 5. Line graph of mean annual grassland yield in relation to mean annual precipitation, mean annual temperature and annual evapotranspiration.

Fig. 7, grass production increases first and then decrease as elevation increases. The maximum grass production is between 3500 and 4000 m, and the lowest grass production is above 5500 m.

Slope affects the absorption of water by grass, and it also has different effects on the distribution of grass production. As shown in Fig. 8, grass production increased as slope increased from 2011 to 2016, with the lowest grass production on the beachfront and the highest grass production on steep slope land.

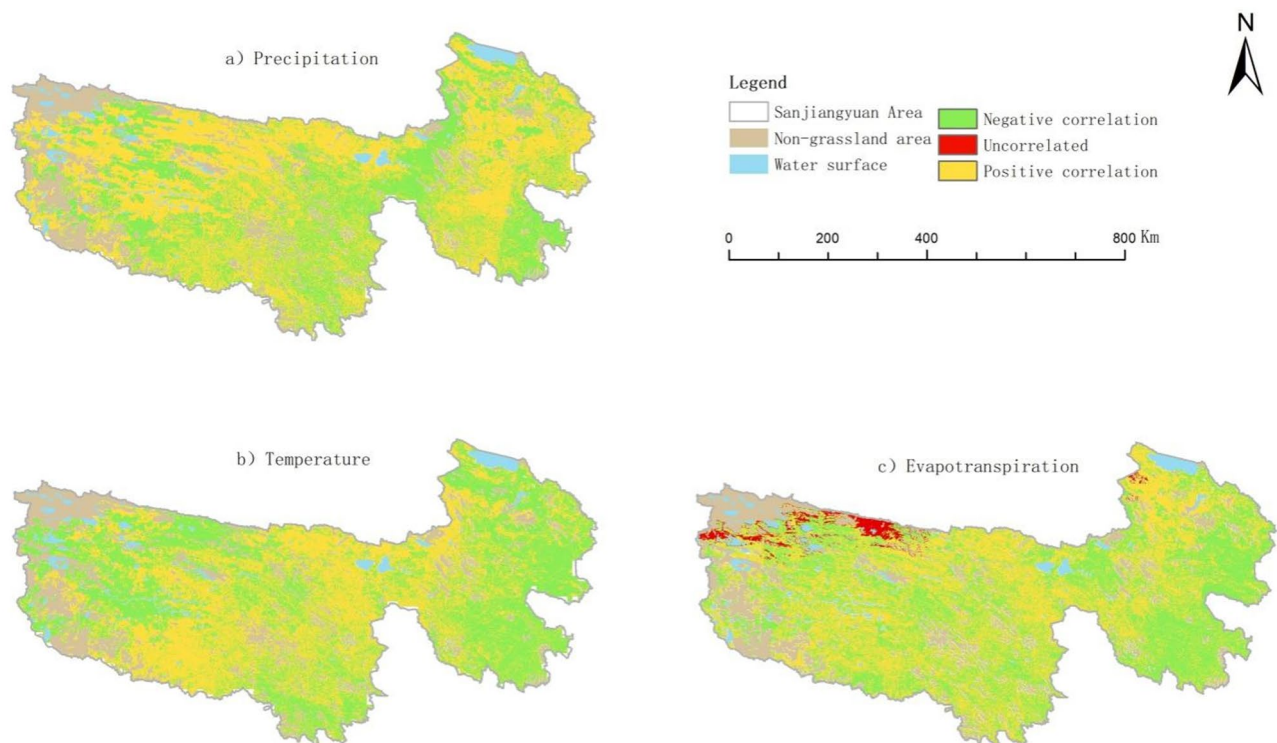


Fig. 6. Partial correlation between grassland yield and precipitation, temperature and evapotranspiration in three river headwater region. the figure was created using ArcGIS 10.7. (URL: <https://prhj.hemaish.com/arcgis?qhclickid=647c456cf883a414>).

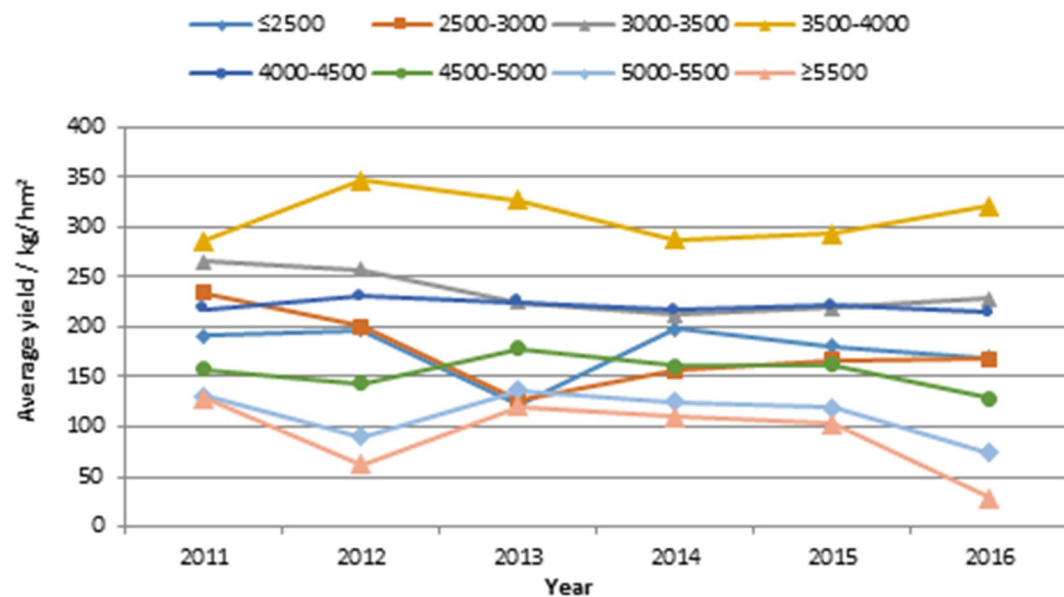


Fig. 7. Relationship between grassland yield and elevation in three river headwater region.

Discussion and conclusions

Discussion

The grassland types in the Sanjiangyuan region are mainly high-altitude meadow, with an average altitude of 3500–4800 m. The grass yield varies greatly in space. According to a study by Fan Jiangwen et al.²¹, the grass yield in the Sanjiangyuan region showed a clear trend of decreasing from southeast to northwest from 1988 to 2005, which is basically consistent with the findings of this study. Li Hongqing et al.²² conducted a study on

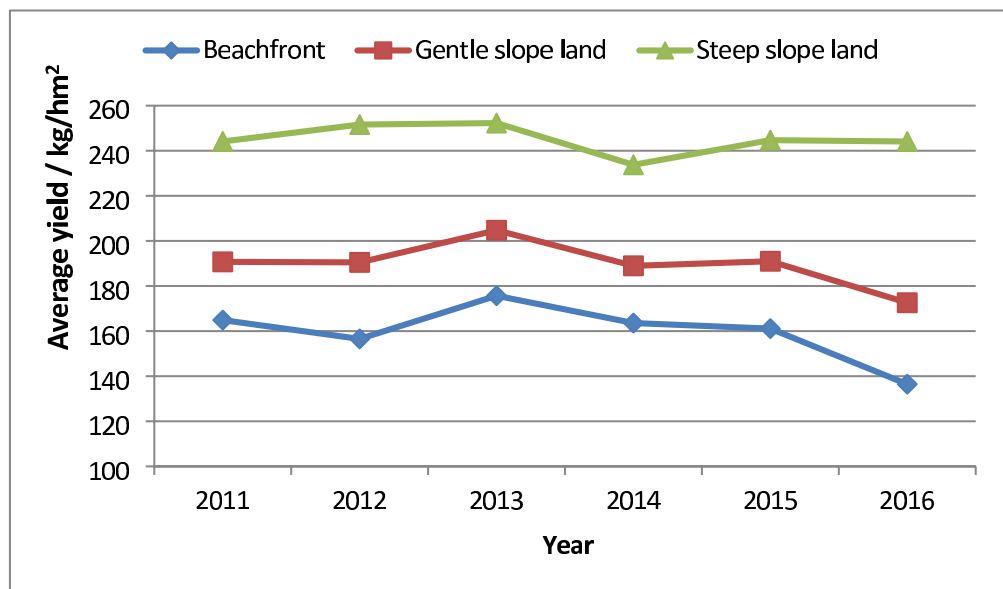


Fig. 8. Relationship between grassland yield and slope in three river headwater region.

grassland ecological protection and reward in Shannan, Tibet, showing that Shannan was in a state of grass-animal balance in 2016–2020, with only minor fluctuations, thanks to the continuous improvement of the grassland ecological protection and reward system in Shannan. Through this study, it can be found that in 2011, Qinghai Province implemented the grassland ecological protection and reward mechanism policy, and through the implementation of the first grassland ecological reward policy, the average grass yield in the Sanjiangyuan region fluctuated around 2000 kg/hm² from 2011 to 2016, with minimal overall fluctuations in space, which is relatively stable. This is also related to the implementation of the ban on grazing, grass-animal balance reward, etc. policies in Qinghai Province.

Our results showed that grassland yield in the Sanjiangyuan region was closely associated with several environmental factors. These correlations would reflect the underlying ecological mechanisms. The significant positive correlation between precipitation and grassland yield might be explained by the fact that water availability is one of the main influential factors for plant growth in alpine ecosystems. As we know, enough rainfall boosts soil moisture that increases plant biomass accumulation, particularly during the short growing season. Temperature and evapotranspiration had weaker correlations with yield in comparison with rainfall. These factors play more complex roles in grassland yield. Higher temperatures generally promote photosynthesis up to a certain threshold. However, it may also increase evapotranspiration rates and reduce soil moisture, especially in regions with not enough rainfall. This may indicate the strong spatial variability in the temperature–yield relationship across the region. Since 2011, the annual precipitation in the Sanjiangyuan region has shown an irregular “M” trend of decline, and the annual average temperature has shown an irregular “W” trend of increase. In 2015, the region experienced extremely high temperatures and less precipitation, which also had an impact on grass production. Liu Peixia²³ et al. used temperature suitability index, moisture suitability index, radiation suitability index, and comprehensive suitability index to study the climate suitability of high-altitude grassland vegetation in the Sanjiangyuan region. The results showed that climate warming increased the vegetation suitability index in the Sanjiangyuan region, but also caused the moisture suitability index to decline, resulting in a decrease in the overall climate suitability index, therefore, climate change is generally developing in a direction that is unfavorable to the growth of high-altitude grassland vegetation. Huo Lili²⁴ et al. conducted a study on the applicability of the evapotranspiration model in the Sanjiangyuan region and proposed the optimal model, indicating that the rational utilization of water resources is of great significance for grass management. Tian Xiaohui²⁵ et al. studied the evaporation characteristics and freeze-thaw changes of degraded alpine meadow in the Sanjiangyuan region, showing that in the case of climate warming, evaporation may increase, thereby affecting the water balance in the region. It can be seen that temperature, precipitation, and evapotranspiration have certain effects on grass production, and precipitation has a positive impact on grassland vegetation in the Sanjiangyuan region. However, in the case of global climate warming, the trends of temperature and evapotranspiration on grassland vegetation are consistent.

Topographic factors (e.g. elevation and slope) strongly influence microclimates, soil depth, drainage, and solar radiation. Moderate elevations (e.g., 3,500–4,000 m) generally provide optimal conditions for grass growth. While extremely high elevations are less favorable for plant growth because of lower temperatures and shorter growing periods. Similarly, steeper slopes may receive more sunlight and face less human disturbance, which contributes to higher grass productivity compared to lowland areas that are more accessible and often subject to grazing pressure. The Sanjiangyuan region has an average altitude of 3,500–4,800 m, and as the altitude increases, the grass yield first increases and then decreases. The maximum grass yield is reached within the range of 3,500–4,000 m. According to the data from the second grassland survey in Qinghai Province, the vegetation types in

the Sanjiangyuan region are mostly alpine meadows, and with the implementation of ecological engineering and grassland subsidy policies in recent years, the grassland vegetation ecology in the Sanjiangyuan region has steadily improved for the better⁶, which is basically consistent with the conclusions in the article. With the increase in altitude and slope, human activities are less, and the damage to the grassland is relatively smaller, which also ensures the stable improvement of grass yield.

Most of our findings are consistent with other studies in alpine and semi-arid grassland ecosystems. For example, Fan et al.¹ reported a spatial gradient in grass yield in the Sanjiangyuan region with a decrease in productivity from southeast to northwest. Similarly, Zhang et al.³ showed the strong effects of precipitation on grassland yield under different subregions and highlighted the key role of water availability in the high-altitude ecosystem. Zhang et al.¹⁴ and Liu Peixia et al.²³ supported our results that temperature and evapotranspiration show weaker and more variable correlations with yield. They pointed out that warming trends can negatively affect vegetation growth due to increased water loss and despite higher energy input. In terms of policy impact, Li et al.²² in Tibet and Ma et al.⁶ on the Qinghai-Tibet Plateau suggested that the ecological compensation policy in Qinghai had a positive effect along with regional environmental conditions. In addition, very recent studies also provide more evidence of ecological and climatic factor effects on grassland productivity on the Qinghai-Tibet Plateau. Zhang et al.²⁶ reported that grazing generally reduced vegetation and carbon storage in soil and noted that moderate grazing could enhance plant productivity. These results supported our findings that the ecological subsidy policy may have stabilized grass yield by reducing grazing pressure. Li et al.²⁷ regenerated vegetation and climate interactions during the Holocene in the northeastern plateau using pollen records. They found out that warm and wet periods were remarkably associated with increased vegetation cover. This historical perspective is in line with our findings related to the positive correlation between precipitation and grassland yield. Furthermore, Wang et al.²⁸ by using showed a negative impact of surface ozone on grassland net primary productivity in China. They suggested the importance of incorporating air quality metrics in future studies of grassland dynamics. Together, these recent contributions reinforce the ecological relevance of our findings and point to valuable directions for future research.

The main results of this study proved that grassland yield in the Three River Headwater Region has stayed relatively stable during the first years of the ecological subsidy policy. This indicates that this policy has played a positive role in controlling overgrazing and improving grassland conditions. It was also found out that precipitation is one of the most important factors affecting yield, indicating that water availability is vital for grassland growth in this region. Elevation and slope also had strong effects on grassland yield and should be considered for planning grassland. These findings can guide local governments and land managers. These results can be used to decide where grassland is more vulnerable and needs to be more protected. In addition, they can improve the balance between grass and livestock by using grass yield data for better grazing plans. We concluded that this study can be used as a reference for future planning and long-term grassland protection in alpine areas.

Conclusion

This study analyzed the spatial and temporal changes in grass production in the Sanjiangyuan region of Qinghai Province based on the first round of grassland ecological compensation in the province. It examined the changes in grass production from both spatial and temporal perspectives, and used this as a basis to analyze its impacts from meteorological and topographic factors.

- (1) Spatially, grass production in the Sanjiangyuan region showed a decreasing trend from east to west. The grass production in the Kuqa Xili area was significantly lower, and the overall spatially stable changes over several years accounted for nearly 87%. From the spatial distribution of grassland types, it can be seen that the grass production in the Sanjiangyuan region forms a clear watershed boundary with high-altitude meadow as the dividing line.
- (2) Temporally, the grass production in the Sanjiangyuan region showed an irregular “M” pattern, with overall fluctuating changes that increased first and then decreased. However, the overall trend was relatively stable, with low fluctuations accounting for a higher percentage, at 51.42%, mainly distributed in the northern, western, and eastern parts of the region, with scattered distribution in the south. Low fluctuations accounted for 30.27%, mainly distributed in the southern part of the region. Medium fluctuations were scattered and intermittently distributed in the northern part of the region. Relatively high and high fluctuations, as well as high fluctuations, accounted for a smaller percentage and were scattered.
- (3) In the Sanjiangyuan region, the area where annual grass production is positively correlated with annual precipitation accounts for nearly 58%, with a concentrated and contiguous distribution. The eastern and northwestern parts of the region are more concentrated, while the southern area has a relatively smaller amount. The area where annual grass production is negatively correlated with annual precipitation accounts for nearly 42%. The area where annual grass production is positively correlated with annual temperature accounts for nearly 48%, while the area where it is negatively correlated accounts for nearly 52%. The area where annual grass production is positively correlated with annual evapotranspiration accounts for nearly 48%, while the area where it is not correlated accounts for nearly 2%, and the area where it is negatively correlated accounts for nearly 50%.
- (4) The grass production in the Sanjiangyuan area increases first and then decreases with the increase of elevation. The grass production is the largest between 3500 and 4000 m elevation. The grass production increases with the increase of slope, and the grass production on the flat land is the lowest, while the grass production on the steep slope is the highest.

Data availability

All data generated or analysed during this study are included in this published article.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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